N62-11100

APR 16 1962

NASA TN D-1044

NASA TN D-1044

TECHNICAL NOTE

D-1044

THE DEVELOPMENT OF THE ELECTRIC FIELD METER FOR THE EXPLORER VIII SATELLITE (1960ξ)

Thomas W. Flatley and Harold E. Evans

Goddard Space Flight Center
Greenbelt, Maryland

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON April 1962

D-1044

THE DEVELOPMENT OF THE ELECTRIC FIELD METER FOR THE EXPLORER VIII SATELLITE (1960ξ)

by
Thomas W. Flatley and Harold E. Evans
Goddard Space Flight Center

SUMMARY

The electric field meter (EFM) was one of the sensors flown in the Explorer VIII satellite launched on November 3, 1960. The EFM, located on the spin axis of the payload, was designed to measure the strength of the electrostatic field caused by the ion sheath surrounding the satellite. Since the sensor required dc motor elements to operate in an ionospheric vacuum, methods were sought to avoid the catastrophic wear rate of standard commercial commutator brushes and ball bearings in a vacuum environment. After an extensive test program, gold-plated stainless steel ball bearings and carbon brushes with a molybdenum disulphide core lubricant were used in the EFM flight units. By using these special components, an EFM was developed with a life expectancy exceeding that of the battery power available.

D-1044

CONTENTS

D-1044

THE DEVELOPMENT OF THE ELECTRIC FIELD METER FOR THE EXPLORER VIII SATELLITE (1960ξ)

by

Thomas W. Flatley and Harold E. Evans

Goddard Space Flight Center

INTRODUCTION

The electric field meter (EFM) shown in Figure 1 was one of several experiments flown in the Ionosphere Direct Measurements Satellite, Explorer VIII. The experimental objective was to measure the electrostatic field strength due to the ion sheath which forms around the satellite as it passes through the ionosphere.

The EFM's sensing element (stator) is a plate which is insulated from the satellite skin and returned to ground through a known impedance. The stator is alternately exposed to and shielded from the electrostatic field by a motor-driven rotor which is grounded to the skin. The magnitude of the field is determined by the measured current passing through the stator impedance.

The primary components of this current are: (1) the current due to the presence of the electric field; and (2) the diffusion current which flows between the medium and the satellite. The first component is an alternating current and is a direct function of both the field strength and the rotor speed. The second component is a function of the diffusion current density and the exposed stator area, and is independent of rotor speed. These two components are 90 degrees out of phase with one another and can be separated by phase discrimination in the associated electronics. The rectifier outputs V_T and V_E reflect both the total current flow and that due strictly to the electric field (Figure 2). A rotor speed of 9000 rpm was sufficient to raise V_E to a conveniently measurable magnitude. The tachometer output used in the phase discrimination also acts as an input to the motor speed control.

The principal design requirements for the sensor were as follows: The stator must be gold plated, insulated from the satellite skin, exposed to the satellite environment, and have a maximum exposed area of at least 20 cm². The rotor must be gold plated, the

D-1044

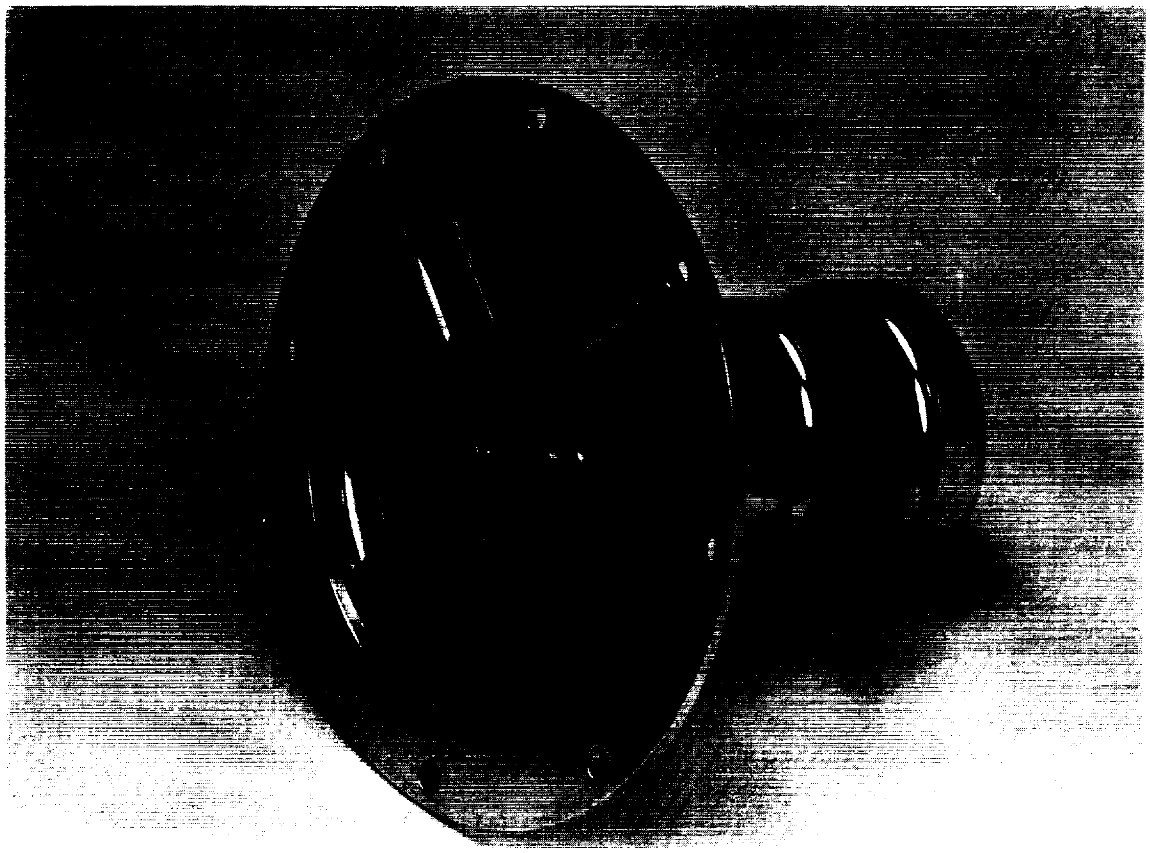

Figure 1 - The electric field meter

same shape as the stator and 3 mm above it, insulated from the motor shaft, grounded to the satellite skin, exposed to the satellite environment, and must rotate at 9000 rpm.

The electrical power in Explorer VIII was provided exclusively by mercury cell batteries. In order to satisfy the EFM life expectancy, the input power during its operation could not exceed 4.5 watts. These factors dictated the use of a small dc motor as the rotor-driving unit.

Two essential elements of a dc motor are ball bearings and commutator brushes. When operated in a high-vacuum environment, both of these elements exhibit catastrophic wear and their useful life is drastically shortened. In the EFM development the basic

D-1044

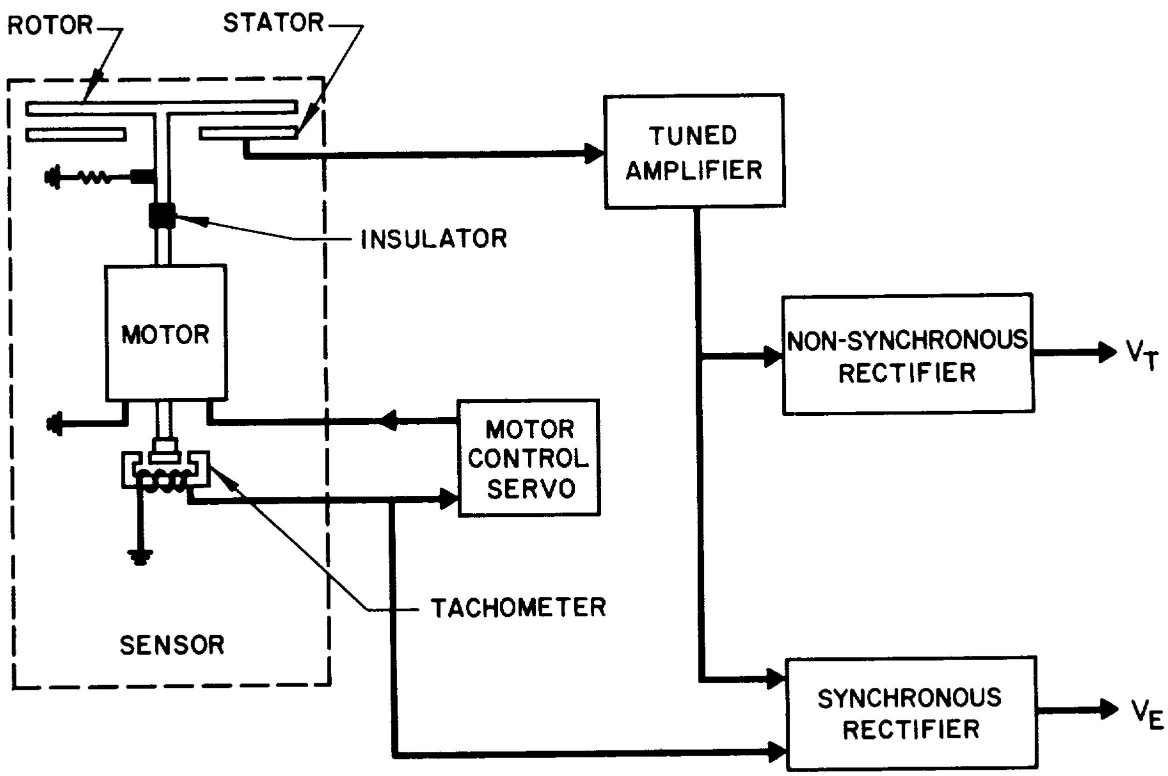

Figure 2 - The Explorer VIII electric field meter experiment

difficulty was the improvement of the dc motor performance in the space environment. Two approaches were considered: (1) to isolate the motor from the environment by sealing the motor drive assembly or by providing a labyrinth path for outgassed molecules to traverse and thereby create a back pressure within the motor housing; or (2) to rework the motor drive assembly so that it would function satisfactorily in the expected environment.

The first approach would involve the development of a vacuum-tight, high speed, low resistance rotary seal. The second would involve the use of novel brushes and bearings to replace standard components. Special brushes and bearings were not available commercially; thus studies were conducted to determine the best brush composition and bearing construction for space applications.

MOTOR SELECTION

Schedule and power requirements limited to two the number of dc motors selected for investigation: the Carter Ecliptic, Type M114E1, 24 v, 9000 rpm, .007 hp; and the Servo-Tek Series A, Type SA-640A-22, 27.5 v, 11,500 rpm, .006 hp. Comparatively, the

Carter motor is much larger and much heavier than the Servo-Tek, but its higher power rating made its use possible if a sealed unit were developed. Both motors use R2 size bearings, but the Carter motor has larger brushes. The Carter brushes are radially mounted and the Servo-Tek are mounted parallel to the armature spin axis. In both cases, the brushes are readily accessible but a bearing change involves complete disassembly of the motor.

Several approaches were studied in the attempts to pressurize the motor. The basic problem was the transmission of the motor armature rotation to the satellite environment. Because of the nature of the experiment, magnetic coupling was not considered. The high speeds involved also ruled out conventional diaphragm or bellows approaches. The possibilities investigated included: low-friction plastic seals; O-ring seals (unlubricated, single lubrication, and continuous lubrication); and minimum clearance seals.

TEST FACILITIES

Available facilities permitted partial simulation of the expected satellite environment. A standard vacuum coating unit was modified for use as the basic test chamber. It has a glass bell jar 18 inches in diameter by 3 feet high, and an oil diffusion type vacuum pump. The lowest ambient pressure attainable was on the order of .01 micron or 10^{-5} torr, which is several magnitudes higher than the anticipated satellite environmental pressures. It was felt that the addition of heat during the testing would make the effective pressure lower than 10^{-5} torr, but the exact correlation between temperature and effective pressure was unknown. A test did prove, however, that the pressure was low enough to evaporate the standard bearing lubricants; but most of the bearings run were degreased before testing as an added precaution.

A heating element was installed in the bell jar for the initial motor tests, most of which were run at an ambient temperature of about 90°C. The running current of the motors was checked by a conventional dc ammeter and the motor speed was determined by using a Strobotac light which shone through the bell jar onto the rotor of the unit. The bearing and motor housing temperatures were measured with copper-constantan thermocouples, whose output was read with a potentiometer.

This basic setup was improved as the testing progressed. A dc milliampere recorder was inserted into the circuit to provide continuous monitoring of the running current, and a millivolt recorder was later used for continuous recording of the temperature variations.

When the tachometer coil became a part of the EFM, its output was used to determine the motor speed. This output was fed into the vertical input of an oscilloscope, and the output of an oscillator was fed into the horizontal input. Since the oscillator output frequency was controllable, the motor speed could be determined by a Lissajous-figure technique.

A cooling coil was also added to the bell jar to permit testing over a wider range of temperatures. This made temperatures below 0°C readily attainable and an ultimate of about -30°C practical. During much of the testing, the ambient temperature was cycled during working hours and then held at either 90°C or below 0°C overnight. No automatic temperature cycling was set up.

Runs of 3 minutes duration were planned for the EFM in orbit, hence a testing sequence of 3 minutes on and 9 minutes off was established. This procedure made the testing more rigorous by providing many stop and start operations for the motor and also gave the motor coil, commutator surface, and bearings an opportunity to cool off between runs. A timer was designed to provide this operating cycle and to permit 24-hour unmonitored testing. The motor speed was not continuously recorded, but it could be approximated by a study of the running-current record.

Many EFM units were vibrated before thermal vacuum testing to assure their structural soundness. The vibration test consisted of two minutes of axial random vibration (20 g rms) and two minutes of radial random vibration (15 g rms) in each of two mutually perpendicular directions.

Periodic checks were also made on the operation of the units as field meters. A potential of 500 volts was applied to a plate mounted 5 centimeters above the rotor face to simulate an electric field of 10,000 volts/meter. The induced charge on the stator was then measured to check the performance.

Figure 3 shows a schematic diagram of the complete test setup.

TEST PROGRAM

The thermal-vacuum test program conducted as a part of the EFM development was divided, in general, into two phases: motor development tests, and EFM prototype tests.

Motor Tests

The motor test program was directed towards the development of a dc motor which would operate satisfactorily in a thermal-vacuum environment. Both the Carter and Servo-Tek motors were run in a vacuum with standard and special bearings and brushes. Both hot (90°C) and cold (-30°C) tests were run. The bearing performance was checked by observing the motor speed and running current, and the brushes were measured before and after testing to determine wear rates. Table 1 provides a general summary of the motor testing performed (see also Appendix A).

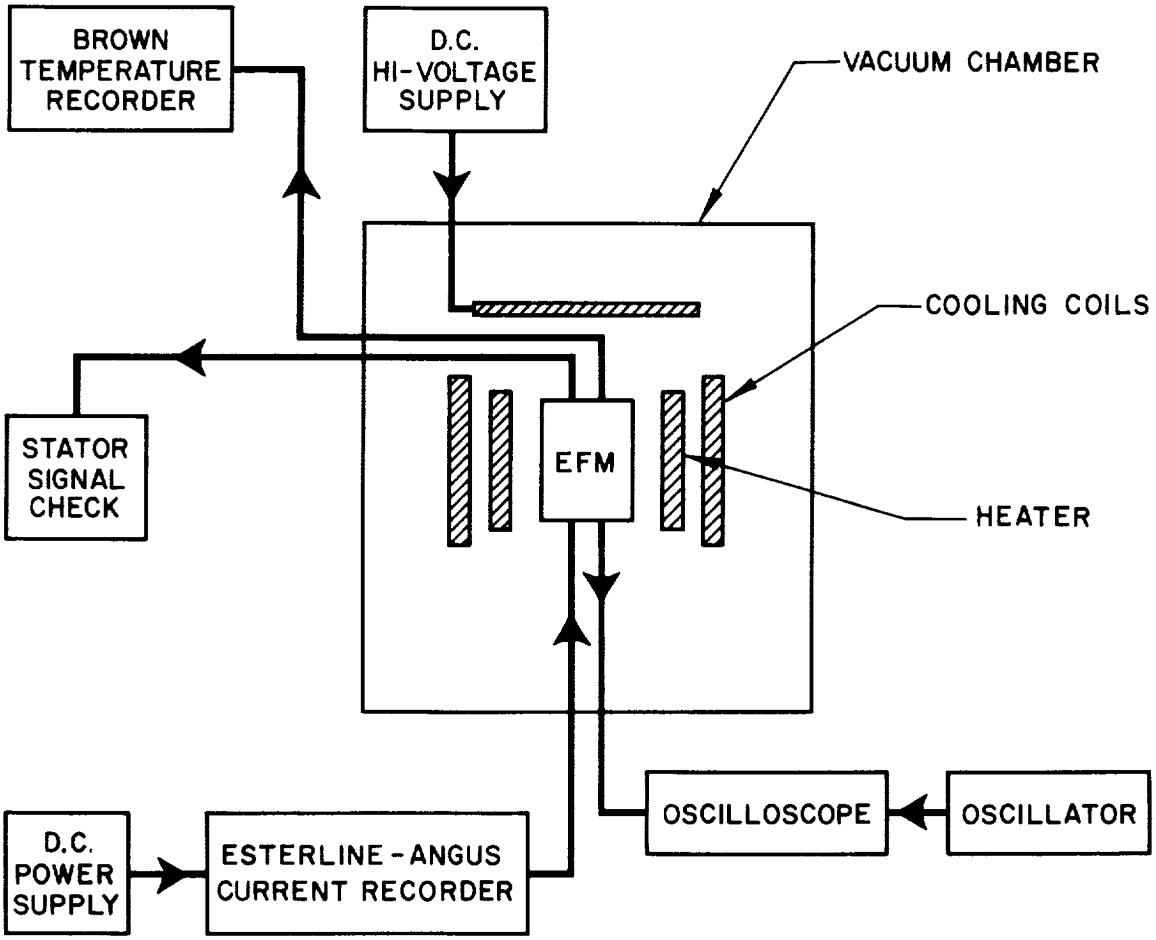

Figure 3 - Schematic diagram of EFM test setup

Prototype Tests

The EFM prototype testing followed the series of motor tests. Here, every unit included the Servo-Tek motor, modified by substituting special bearings and brushes. The inclusion of vibration and of temperature cycling made the testing more rigorous. Table 2 summarizes the prototype testing results (see also Appendix B).

SIGNAL SEPARATION

One of the main problems in the EFM design involved the separation of the stator signal due to the electric field from that due to the diffusion current. These two signals are 90 degrees out of phase. Two approaches were considered: the signals could be separated mechanically by a commutator device, or electronically by phase discrimination. A mechanical separation would make accurate motor speed control unnecessary,

Table 1
Motor Test Summary

Test No.	Motor	Brushes	Bearings	Pressure (torr)	Temp. (°C)	Running Time	Brush Wear (inches/hr)	Results and Comments
1	Carter	Standard	Standard	3×10^{-5}	90	5 sec		Motor shaft bent as test was started; rpm was near the shaft/rotor critical speed
2	Carter	Standard	Standard	3×10^{-5}	90	4.5 hrs	.013	Extreme brush wear caused failure; unit performance was noisy and erratic
3	Servo-Tek	Standard	Standard	3×10^{-5}	90	12 min		Motor shaft bent as before; shaft/rotor coupling redesigned after this test
4	Servo-Tek	Standard	Standard	10^{-5}	90	26.5 hrs	.000	No failure; performance excellent; brushes sprayed heavily by oil from the bearings
5	Servo-Tek	G.E. Carbon MoS_2 Lube	Ind. Tect. Tool Steel	10^{-5}	90	2.5 hrs	<.001	Commutator lost solder due to heat build-up caused by friction in the dry steel bearings
6	Servo-Tek	G.E. Carbon MoS_2 Lube	NHBB Gold (Synthane)	10^{-5}	90	21 hrs	<.001	No failure; bearing and brush performance excellent although retainer wear was great
7	Servo-Tek	G.E. Carbon MoS_2 Lube	NHBB Gold (Alum)	10^{-5}	90	32 min	<.001	Commutator lost solder; brush overload at assembly caused very high running current
8	Servo-Tek	G.E. Carbon MoS_2 Lube	NHBB Gold (Synthane)	10^{-5}	90	14.5 hrs	<.001	Test halted when rotor separated from shaft; brush and bearing performance excellent
9	Servo-Tek	Stackpole Cu Lube	NHBB Gold (Alum)	10^{-5}	90	5 hrs	<.001	Commutator lost solder although unit did not overheat; apparently defective commutator
10	Servo-Tek	Stackpole MoS_2 Lube	NHBB Gold (Synthane)	2×10^{-5}	90	31 hrs	.002	Commutator again lost solder; brush wear high; bearing performance excellent
11	Servo-Tek	G.E. Carbon MoS_2 Lube	Ind. Tect. Tool Steel	10^{-5}	90	6 hrs		Two sections thrown from resoldered commutator; no melting of solder; unit overheated
12	Servo-Tek	G.E. Carbon MoS_2 Lube	NHBB Gold (Alum)	10^{-5}	90	60 hrs	<.001	No failure; bearing and brush performance excellent; unit used resoldered commutator
13	Servo-Tek	Stackpole Ag Lube	N. D. All Stellite	10^{-5}	-10	15 min	.030	First cold test; lost commutation; very high brush wear, brushes stuck in place afterward
14	Servo-Tek	Stackpole MoS_2 Lube	N. D. Teflon and Stellite	10^{-5}	-10	1 hr	.037	Lost commutation; very high brush wear; randomly impregnated brushes seem poor
15	Servo-Tek	G.E. Carbon MoS_2 Lube	N. D. Teflon and Stellite	10^{-5}	-20	15 min	.003	Lost commutation; brush wear higher than usual for this type of brush
16	Servo-Tek	G.E. Carbon MoS_2 Lube	N. D. All Stellite	10^{-5}	-30	9 hrs	.002	Lost commutation; brush wear again higher than normal; brushes apparently stuck in holders
17	Servo-Tek	G.E. Carbon MoS_2 Lube	NHBB Gold (Alum)	10^{-5}	-30	108.5 hrs		Commutator lost solder and fell apart; bearing performance excellent; brushes destroyed
18	Servo-Tek	G.E. Carbon MoS_2 Lube	NHBB Steel E.K. Lube	10^{-5}	90	1.5 hrs	.001	Commutator lost solder due to overheating caused by high bearing friction; lubricant poor
19	Servo-Tek	G.E. Carbon MoS_2 Lube	NHBB Steel E.K. Lube	10^{-5}	90	6.5 hrs	.001	Bearing crown retainer spread and jammed; this type of bearing apparently no good in vacuum

Table 2
Prototype Test Summary

EFM Prototype No.	Description	Running Time (hours)	Ambient Temperature (°C)	Ambient Pressure (torr)	Results and Comments
1	First fully instrumented electric field meter	1.3	20	10^{-4}	Rear bearing not fully seated during assembly and came apart during vibration and start of testing
2	Included a bakelite rear bearing shield	7.2	-10 to 90	8×10^{-5}	Contraction of the bakelite shield when cold was applied caused mechanical interference
3	Included a teflon shield over the rear bearing	0.6	0 to 90	10^{-4}	Interference between the shield and the motor shaft again curtailed the test
4	New bearings and new motor; no shield used	13.5	0 to 90 6 cycles	10^{-5}	10 hrs excellent performance; brush wear very low; bearing retainer wear caused stoppage
5	Newly designed housing; new brushes and bearings	1.9	100+	10^{-4}	Unit accidentally overheated, causing a loss of solder from the commutator and failure
6	Same as No. 5 except for new motor armature	2.6	-10 to 90	10^{-4}	Motor failed to start after 52 excellent 3-minute runs; lost commutation
7	New brushes and used bearings; same housing	9.4	-30 to 90	8×10^{-5}	Bearing retainer wear caused failure; apparently one group of bearings received were defective
8	Unit built from all used components	11.5	-30 to 90 5 cycles	8×10^{-5}	Bearings contaminated by brush carbon and worn somewhat; performance good during most of test
9	Same as No. 8 except for new armature; bearings cleaned	7.5	0 to 90 3 cycles	8×10^{-5}	Motor performance deteriorated due to contamination of bearings and interference problem
10	Same as No. 9 except step on shaft was chamfered	4.0	0 to 90	8×10^{-5}	Unit failed to start after 80 3-minute runs; lost commutation
11	Same as No. 10; motor started with a push	2.5	0 to 90 2 cycles	8×10^{-5}	Unit stopped after bearing condition worsened; bearings were part of defective shipment
12	Used tool steel bearings and a Kel-F bearing shield	4.2	0 to 90 2 cycles	7×10^{-5}	Tool steel bearings proved unacceptable; bearing shield was partially effective
13	Included used gold-plated bearings and bakelite shield	4.0	20	7×10^{-5}	Lost commutation after 80 runs; close examination revealed cause of similar failures during program
14	Used standard bearings and brushes and Kel-F shield	1.8	0 to 90 2 cycles	7×10^{-5}	Rapid failure; extreme brush wear provided good carbon distribution pattern to guide housing redesign
15	Used bearings and new brushes; bakelite shield	24.6	-30 to 90 12 cycles	6×10^{-5}	Gradual failure due to bearing retainer wear; brush performance excellent; shielding very effective
16	New bearings; final design electric field meter	60.0	-30 to 90 27 cycles	6×10^{-5}	Unit performance excellent; bearing wear slight; brush performance excellent; shielding very effective

while electronic separation would require more complicated electronics and the development of a synchronous wave through a tachometer-like device. This wave would be used as a reference for separating the signals, for determining the polarity of the signals, and as the input to the motor-speed control circuit.

Mechanical separation was investigated first. In all cases, the design involved a cylindrical commutator, revolving under fixed contacts, which acted as a switch and permitted alternate sampling of the two signals measured. The basic requirement was for the commutator to rotate with the motor armature (at approximately 9000 rpm). Riding on the commutator were three brushes or wipers (one common and continuous, and two alternately opening and closing). The requirement was for both alternating contacts to be opened and closed 4 times per commutator revolution on a 50 percent duty cycle. The closing of the two contacts were to be 22-1/2 mechanical degrees out of phase.

A sample commutator design is shown in Figure 4. An insulating material was to be molded or machined to fit the commutator and complete the cylinder. Sample commutators were made of stainless steel, copper, brass, coin silver, aluminum, and aluminum bronze. Insulating materials tried included fluorosint, Kel-F, stycast, castaplate, diallyl phythylate and lava. Contact materials used included Ney-Oro-G wire, standard carbon brushes, MoS_2 lubricated carbon brushes, music wire, copper wire, silver-graphite brushes and nickel-graphite brushes.

The problems encountered included: (1) Contacts bouncing on the commutator because of high speed and lack of perfect concentricity (causing noise and discontinuities); (2) Rapid wire wear; and (3) Smearing of carbon on the insulating material, which resulted in a conducting film on the face of the insulation.

The first mechanical separation device designed for use on the EFM — the sequential grounding device — incorporated grounding wires cemented to set screws and supported by bakelite rings. A fixed ring supported the continuous ground wire and one of the sequentially grounding wires, and an adjustable ring supported the third wire; the latter was necessary for control of the phase between the two grounding wires. In this case, the commutator was a 1/4-inch-diameter cylinder.

When the grounding-wire approach proved impractical because of accelerated wire wear due to the high surface speeds involved, another unit was designed which incorporated brushes. This unit was basically the same as the previous device, but the greater contact area of the brushes made a larger commutator necessary. In this case, brushes similar to the motor-power brushes (MoS_2 lubricated) were supported in teflon rings and one brush position was adjustable.

After several commutator-material combinations were tried and some manufacturers of commutation devices were contacted, it was decided that the surface speeds

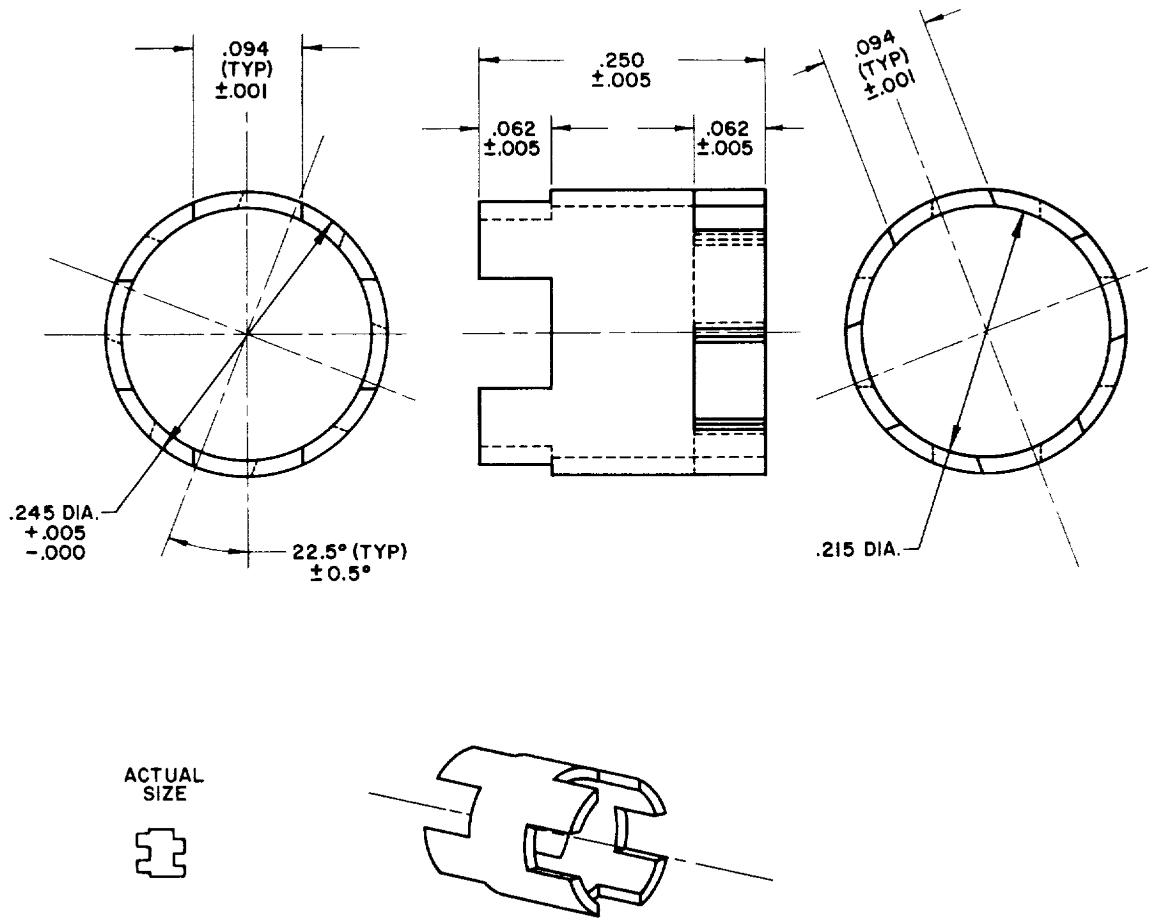

Figure 4 - Sample commutator design

involved made the development of a satisfactory mechanical signal-separation device improbable; therefore, the efforts were redirected towards electronic separation.

Mechanically, the electronic separation was simpler, since it merely involved a magnetic circuit whose reluctance varied with the motor armature position. The design consisted of a small, contoured iron wheel attached to the rear shaft of the motor, a coil wound on an Alnico V magnet, and magnetic stainless steel coil-supports which completed the circuit. As the wheel rotated, an alternating voltage was developed across the coil; this voltage frequency was equal to four times the motor speed (because of the wheel contour) and the magnitude was a direct function of both motor speed and magnet strength.

The use of a permanently magnetized wheel and an iron core for the coil was considered but rejected in favor of the simpler design.

DESCRIPTION OF FINAL DESIGN

The EFM weighs 8-1/2 ounces and requires a power input of approximately 1.5 watts. The external appearance of the final EFM design is shown in Figure 5. Figure 6 shows a partially disassembled meter and illustrates the housing, rotor, stator, reworked motor, and tachometer.

All EFM units installed in the various satellite payloads were checked in the vacuum chamber before delivery. The EFM's installed in the satellite prototypes and flight models did not require servicing during prototype testing, flight testing, or launch preparations. No design changes were made between the delivery of the prototypes and the delivery of the flight units.

The final design for the EFM flown on Explorer VIII consisted of the following items.

Drive Mechanism

The drive mechanism was a Servo Tek SA-640A-22 dc motor with the following modifications:

(1) The aluminum front-end piece was trimmed to reduce the overall length of the motor and in turn reduce the amount of shimming required to eliminate shaft end-play.

(2) The bakelite end piece was sculptured to permit freer escape of brush particles from the rear bearing area, drilled and tapped for tachometer coil support mounting, drilled to permit the extension of the rear shaft of the motor, and drilled and counter-bored to change the location of the assembly screws. Also, the raised lettering was removed from the back of the end piece to provide a flat surface for mounting the tachometer coil.

(3) The housing was slotted to permit the escape of carbon particles from the area of the rear bearing.

(4) A longer rear shaft was added to the armature to support the small wheel of the tachometer, the shoulder behind the bearing was cut back on both the front and rear shaft to eliminate a possible interference problem, and the front shaft was drilled and tapped for the rotor mounting screw.

(5) An aluminum foil tape shield was cemented to the bakelite rear-end piece as a shield for the rear bearing.

(6) The standard motor brushes were replaced by special MoS_2 -lubricated brushes.

Figure 5 - Final EFM design

(7) The standard bearings were replaced by special unlubricated gold-plated bearings. Bushings were also required since the new bearings were smaller than the original type.

(8) A filter circuit was added to the motor power terminals to eliminate the electrical noise originating at the brush contact points on the commutator. The circuit consisted of a capacitor and a choke coil which were supported by the bakelite standoffs which also supported the tachometer coil. The motor's negative power terminal was also grounded to the housing.

Housing

The main housing, made of gold-plated aluminum, was mounted to the satellite instrument column and supported the motor, the stator, the rotor grounding brushes, and the electrical connectors.

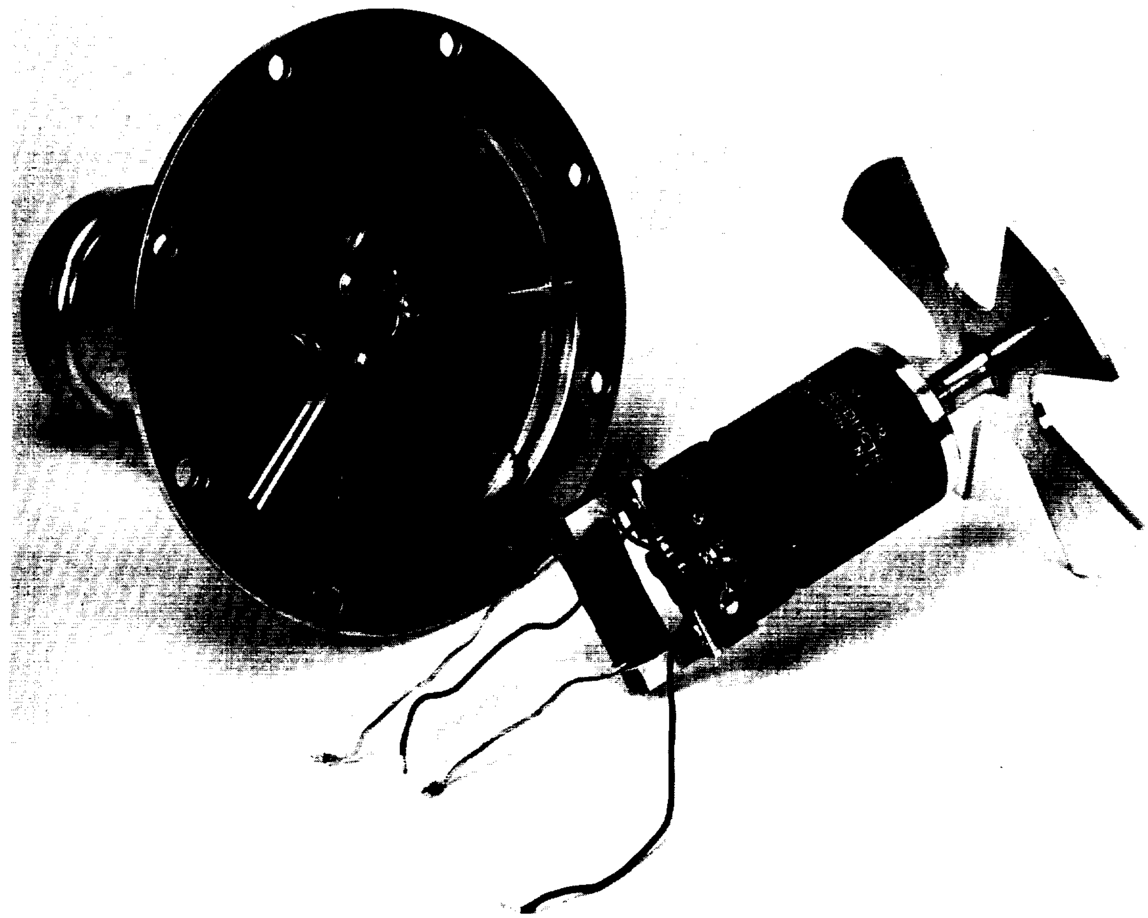

Figure 6 - Disassembled EFM

Rotor-Stator

The 4-inch-diameter four-bladed rotor used was made of gold-plated aluminum. It was mounted to and insulated from the front shaft of the motor, and grounded to the main housing through three MoS_2-lubricated carbon brushes. The gold-plated aluminum stator has the same contour as the rotor and is mounted to and insulated from the main housing.

Tachometer

In the tachometer, the aft wheel, made of soft iron, is mounted to the rear shaft of the motor. This is the moving component of the tachometer circuit mounted on the rear of the motor. The rest of the circuit consists of a coil wound on a permanent magnet (Alnico V) core and supported by legs made of magnetic stainless steel.

Electrical Connections

The EFM electrical connections are made through two connectors. The shell of a standard Microdot connector is grounded to the main housing, and the center pin is wired to the underside of the stator. The two motor power leads and the two tachometer coil leads are wired to a standard Continental connector mounted near the aft end of the housing.

RESULTS AND DISCUSSION

Brush Testing

The brushes were important in three different aspects of the EFM development – rotor grounding, mechanical signal separation, and dc motor commutation. Types of brushes tested included:

Standard carbon
Carbon with a MoS_2 lubricating core
Carbon with a random MoS_2 impregnation
Carbon with a random silver impregnation
Carbon with a random copper impregnation
Silver-graphite, and
Nickel-graphite.

Most of the testing was done in a vacuum environment, but an attempt was made to simulate the effects of vacuum by testing the brushes in an atmosphere of flowing dry nitrogen. The presence of water vapor seems necessary for the efficient operation of standard carbon brushes, and it was hoped that the dry nitrogen atmosphere would prevent replenishment of the water vapor content of the brushes and thereby simulate vacuum conditions (Appendix C). Nitrogen from a standard high pressure bottle passed through a drying agent (silica gel) before entering the test chamber. After no correlation was found between the performance of the brushes run in the nitrogen tests and similar samples tested in the vacuum chamber, dry nitrogen testing was abandoned.

Standard carbon brushes quickly proved totally unacceptable for vacuum operation. The first special brushes tested were carbon brushes made by General Electric with an MoS_2 core, and they were the outstanding brushes used throughout the EFM development. Wear rates of less than .001 inch/hour were consistently attained with this brush. Limited tests were performed with the other special brush types mentioned, but none seemed to approach the efficiency of the MoS_2 core brush.

There were several uncontrolled variables in the testing which could effect brush performance, e.g., commutator design and surface finish, and amount and distribution of spring loading. The performance of the MoS_2 core brushes, however, was excellent under all conditions, and they were used both for rotor grounding and for motor commutation. No brushes were required in the final signal separation design.

Bearing Testing

In the EFM development, the bearings tested included:

Standard Swiss RMB-RF-310 (standard in Carter motor)

Standard New Departure ND77R2 (standard in Servo-Tek motor)

Standard New Hampshire SFR166PPX

Industrial Tectonics R3-HA-564 (all tool-steel)

Industrial Tectonics R2-HA-564 (all tool-steel)

Special New Hampshire R2-5 (gold-plated balls and races, synthane retainer)

Special New Hampshire R2-5 (gold-plated balls and races, anodized aluminum retainer)

New Departure X-01456-R2 (all stellite)

New Departure X-02206-R2 (stellite with teflon slug separators between the balls)

New Hampshire SR166K34 (440C stainless steel balls and races with special oil diffusion coating)

New Hampshire SR166K34 (52100 steel balls and races with special oil diffusion coating).

After it was seen that the ambient pressure attainable in the test chamber was not low enough to "dry out" a well lubricated, shielded bearing in a reasonably short time, all bearings tested were degreased by a benzene vapor process. After degreasing, all standard bearings proved totally unacceptable.

One approach to bearing operation in a vacuum involves the use of low-shear-strength metals as lubricants (Appendix D). Bearings of this type, in particular the gold plated bearings, proved most acceptable in the tests.

Among the other types of bearings tested, only the stellite bearings with teflon slug separators seem worthy of further evaluation. The two tests run with this type of bearing were shortened by motor commutation difficulties and time did not permit further study.

The weak link in the gold-plated bearings seemed to be the retainer. Of the two types tested, the anodized aluminum retainer seemed superior to the synthane, but neither is likely to be reliable for long term high speed operation. The gold plated bearing with the anodized aluminum retainer was satisfactory for the EFM, however, since the satellite lifetime was quite limited.

CONCLUSIONS AND RECOMMENDATIONS

In the test program, the most acceptable substitute for standard bearings and brushes in order to improve dc motor operation in a thermal-vacuum environment were found to be the gold-plated stainless steel ball bearings with a solid machined retainer of anodized aluminum; and the carbon brushes with a core of molybdenum disulfide. Under ambient temperatures of -30° to 90°C and pressures on the order of 10^{-5} torr (in an oil pump system) the brush life expectancy is 300-400 hours and the bearing life is approximately 100 hours.

The successful bearing operation during EFM testing encourages further study of low-shear-strength metals as dry bearing lubricants, particularly since the weak link seemed to be the retainer. A program will be undertaken for the purpose of finding the best retainer material, and also the best type of ball and race plating for long term vacuum operation of bearings.

Phase I of the planned program will study different retainer materials. All balls and races in this series of tests will be gold plated stainless steel. Phase II will study the performance of various types of plating for the balls and races, and all bearings will employ the retainer type chosen from Phase I.

Future bearing tests will be run in an oil-free vacuum system in which sorption type roughing pumps and ion-type high vacuum pumps will be used.

In this type of system component lubrication by diffusion pump backstream oil, an unknown variable during EFM testing, will be positively eliminated and attainable pressures will be on the order of 10^{-7} or 10^{-8} torr.

ACKNOWLEDGMENTS

The authors wish to thank New Hampshire Ball Bearings Inc., for making available the information which they had accumulated on the problem of bearing operation in a vacuum and for supplying, without charge, the test and flight bearings for the EFM; and the General Electric Corporation Research Laboratories for freely discussing the bearing and brush problem and for making Dr. W. E. Campbell available for consultation on this problem.

Appendix A

Motor Test Data

High Temperature Tests in a Vacuum

The Carter Motor

The first item studied in the development of the electric field meter was the performance of the Carter motor in a vacuum environment. A six-bladed rotor was mounted to the motor shaft and the unit was set up in the vacuum chamber. After the temperature was raised to 90°C., voltage was applied to the motor and almost instantaneously, the motor shaft bent and the power was cut.

While the cause of this failure was being investigated, another similar unit was set up in the vacuum chamber (Figure A1). This unit ran for 4-1/2 hours, three minutes at a time, but then failed to start because of catastrophic brush wear. While in operation, the unit was noisy and its running current was erratic but the bearing temperature did not rise excessively during the runs.

The Standard Servo-Tek Motor

The next test investigated the performance of the standard Servo-Tek motor in a vacuum. The same 6-bladed rotor was mounted to a standard unit which was placed in a vacuum and heated to 90°C. This unit was also run for 3 minutes at a time and its shaft bent near the end of the fourth run (Figure A2).

The two shaft failures and the noisy performance of the second test unit were explained after a rough calculation of the natural frequency of the rotor-shaft combination being used. This was found to be about 150 cps which was very close to the running speed of both motors. This caused an amplification of the unbalance in the units which led to the failures. The rotor-shaft combination was then re-designed to raise its natural frequency above the danger level.

The next unit tested consisted of a Servo-Tek motor with a modified shaft which was coupled to a new 4-bladed rotor (Figure A3). This unit was also run at 90°C. in a vacuum. The test lasted 26-1/2 hours – 530 three-minute runs – before it was stopped. No failure had occurred. The standard carbon brushes showed little evidence of wear, but were soaked in oil which had come from the motor bearings.

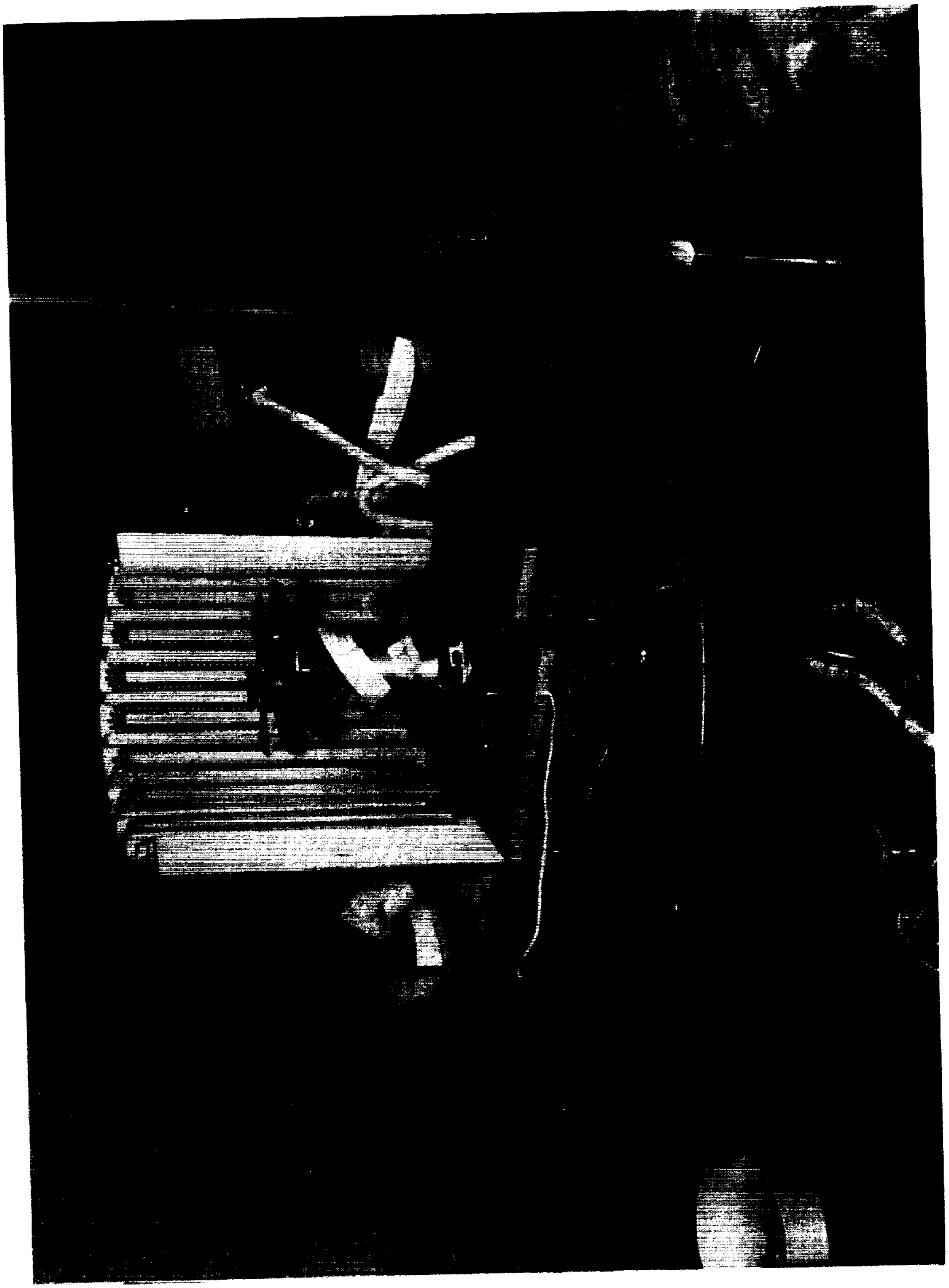

Figure A1 – The Carter motor under test

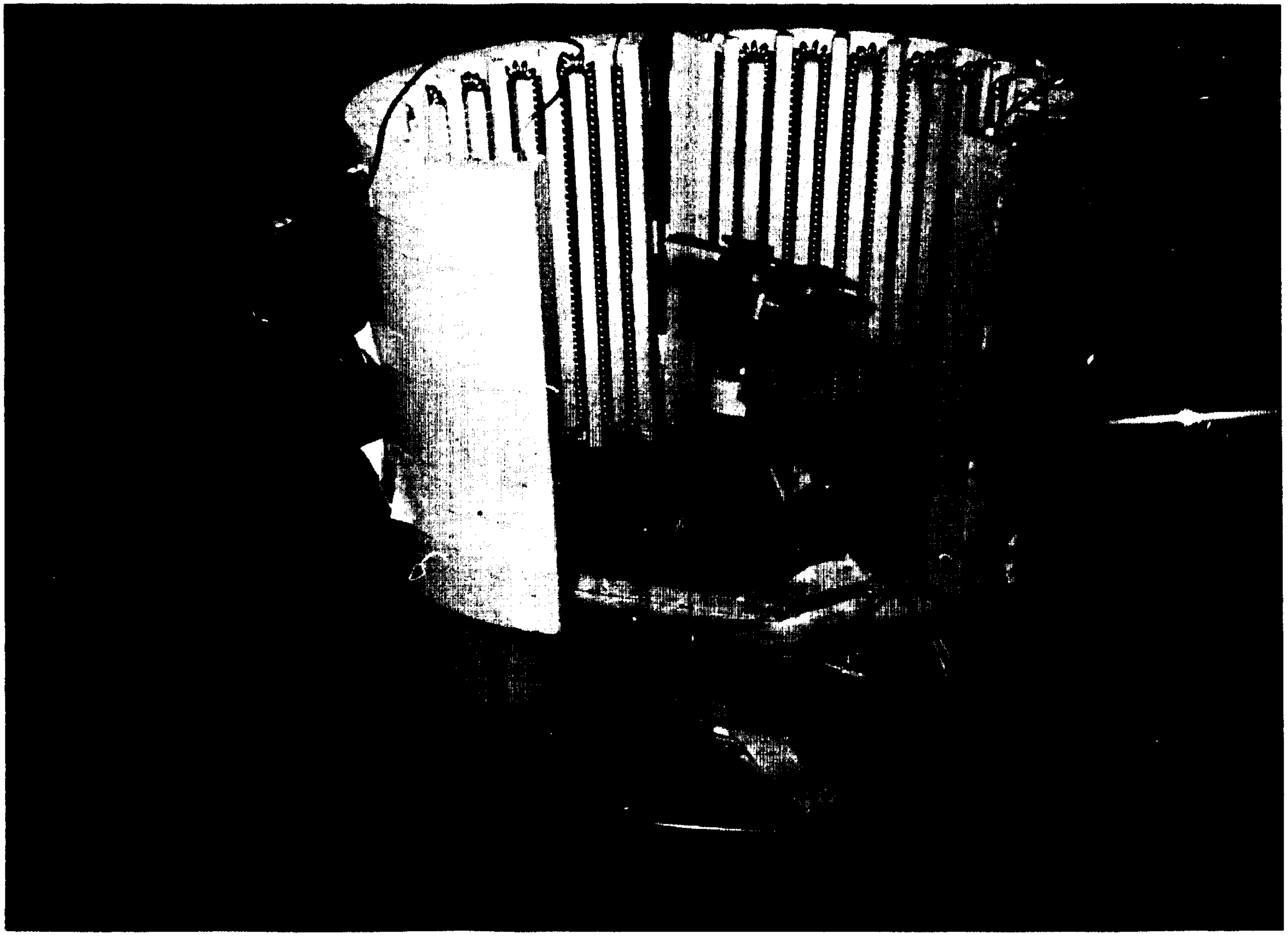

Figure A2 - The Servo-Tek motor with bent shaft

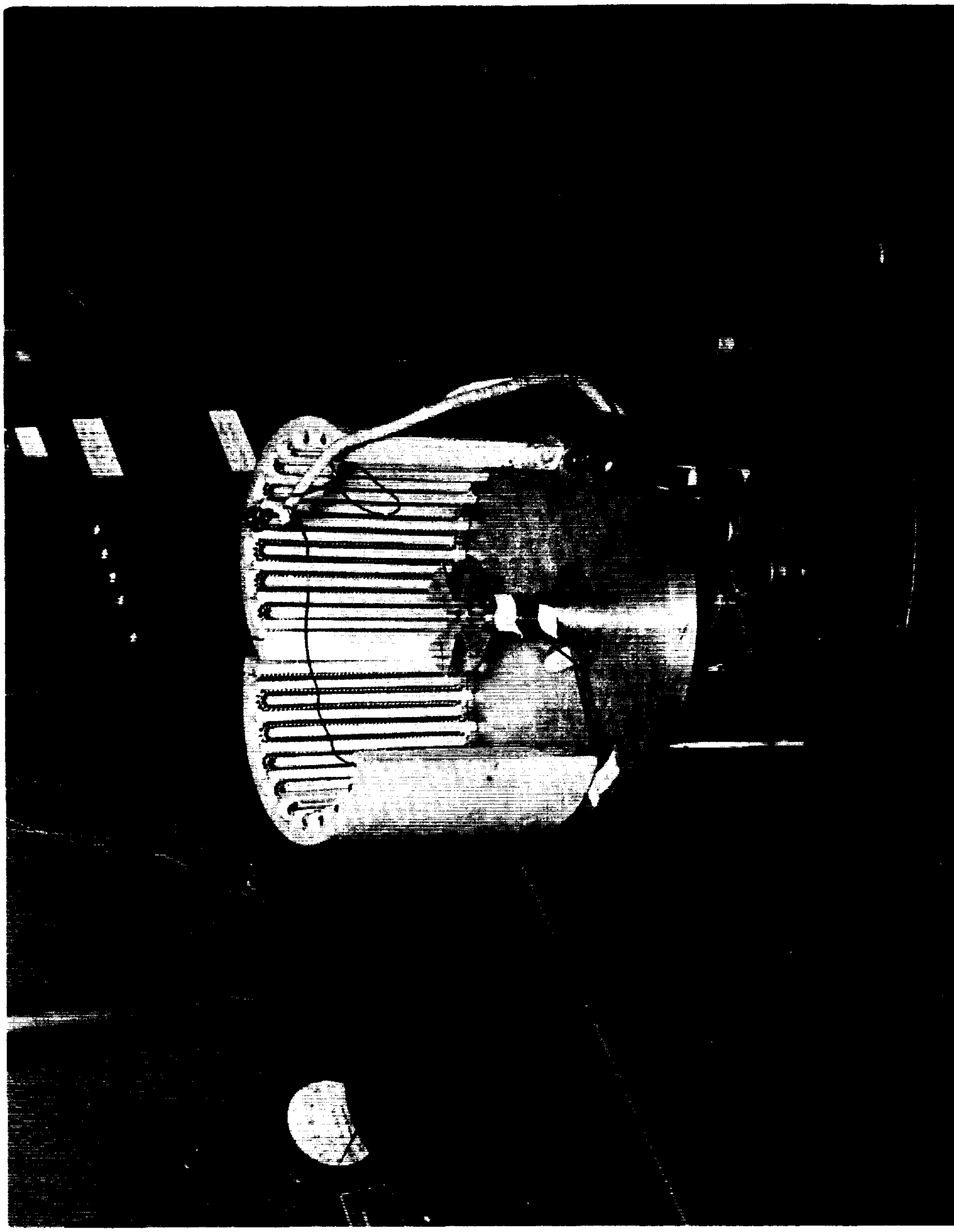

Figure A3 - EFM unit with four-bladed rotor

During this early testing, a pressurized EFM was being fabricated. It incorporated a double O-ring seal, and was adaptable for use with either of the motors. Attempts were made, using both motors and various O-ring compressions, to build a unit which would perform satisfactorily while maintaining a 15 psig pressure inside. All attempts resulted in erratic motor speed, or no positive seal, or a resisting torque too great for the motors to overcome. After it was decided that sealing was not practical in this application, all efforts were directed to the development of the smaller, low-power Servo-Tek motor for use in the EFM.

As an initial step, the retainers were removed from the standard bearings used in the motor, and the bearings were degreased using a benzene vapor process. After careful assembly, the motor was started on the bench and in about a minute's time the bearings seized. It was concluded, therefore, that the standard bearings required lubrication, even outside the vacuum and at room temperature.

Since sealing the motor appeared impossible, and the degreased unit had failed so rapidly, a design was studied which included lubricated bearings and a minimum clearance between the motor shaft and the housing instead of a mechanical seal. A unit was fabricated and tested briefly, but without much success and the minimum clearance approach was then shelved.

Dry Bearings

At this time, some bearings were made available which offered the possibility of dry operation. The first dry bearings tested were made entirely of M2 tool steel. They were degreased and assembled in a Servo-Tek motor and the unit was set up in the vacuum chamber. This unit was run at 90°C. for 53 three-minute periods and then failed to start for the 54th run. The test was marked by a large increase in bearing temperature during the runs, and a steady deterioration of motor performance. Disassembly revealed that the solder in the motor armature had melted, which allowed the coil wires to separate from the commutator. This unit was the first to use non-standard brushes. Carbon brushes with a MoS_2 core were used, and the results of this first test were encouraging. The wear rate was less than .001"/hour.

The next bearings tested were made of gold-plated steel except for the retainer, which was machined from synthane. These bearings were assembled in a motor using MoS_2 lubricated brushes, and were tested without an EFM rotor. The unit was initially heated to 90°C. and given 88 three-minute runs, during which the motor performance was excellent. It was then decided to make longer runs, and the unit was run for an over-all total of 21 hours. The last run alone lasted about 6-1/2 hours. No failure was experienced. Brush wear was only .0003"/hour. The bearings were returned to the manufacturer for inspection, and the retainers were found to be in poor condition. The temperature rise in the bearings was small.

Similar gold-plated bearings, with anodized aluminum machined retainers, were tested in a motor under load (with a rotor). An assembly error resulting in a brush overload slowed down the speed and caused the running current to rise excessively. Solder was melted and thrown from the commutator; the total running time was only 32 minutes. The wear on the MoS_2 lubricated brushes was still less than .001"/hour, however.

Another test was then run on the synthane retainer bearings, this time under load. The unit was heated to 90°C. and then run for a total of 14-1/2 hours, one hour at a time. The test ended when the rotor separated from the motor shaft. The motor performance was excellent throughout the test but the retainers showed signs of considerable wear. Brush wear was again very low.

Brushes with Random Impregnation

By this time other special brushes were made available and although the MoS_2 lubricated brushes appeared acceptable for use in the EFM, the next motor tested used carbon brushes with a random copper impregnation, with gold-plated bearings and anodized aluminum retainers. This unit was run under load, and lasted for 5 one-hour runs, during which the solder from the commutator again melted. Since no excessive temperatures had been recorded during the test, and nothing unusual was noticed, it was assumed that a poor solder has been used in the latest shipment of motors received. The manufacturer was notified and arrangements were made to improve the quality of solder used in future motors. Bearing performance was excellent and brush wear was also good — less than .001 inch/hour.

Another test was set up with the synthane retainer gold-plated bearings, and carbon brushes with a random MoS_2 impregnation. This unit was tested in the vacuum, at 90°C., and for 1-hour running periods. The unit ran for 31 hours and lost solder from the motor commutator. The motor used was from the same shipment as the one used in the previous test. Bearing performance again was excellent even though the one nearer the motor commutator had been considerably contaminated by brush carbon. Brush wear was relatively high, .002 to .003 inch/hour.

After inspection of the gold-plated bearings by the manufacturer, it was concluded that the anodized aluminum retainers were the better of the two types tested, and the testing of the synthane retainers was discontinued.

Resoldering of Commutators

A test was then run to check the acceptability of resoldering commutators with high-temperature solder. A unit was set up in the vacuum using the MoS_2 lubricated brushes and a pair of the all tool steel bearings. This unit was run under load, and at 90°C., for

1-hour periods and lasted for 6 hours. Failure occurred when two sections of the motor commutator broke away, thereby destroying the brushes. The bearing temperature rise was considerable but no melting or loosening of the solder was noticed; however, the heat required to re-solder the armature apparently had weakened the commutator segments.

Another armature was re-soldered and assembled in a unit using gold-plated bearings and MoS_2 lubricated brushes. One-hour runs were made in the vacuum, at 90°C. The unit performance was excellent throughout 60 hours of operation. Bearing temperature rise was small and brush wear was approximately .0005 inch/hour. This resoldering operation had not had an adverse effect on the armature.

On the basis of the tests completed, it was decided that the gold-plated steel bearings with a solid machined anodized aluminum retainer and also the MoS_2 lubricated carbon brushes would meet the high temperature performance requirements of the EFM.

Low Temperature Motor Test in a Vacuum

Stellite Bearing Tests

Next, cold testing of the motors was undertaken. Refrigeration coils in the vacuum chamber provided an ultimate temperature of about -30°C. By this time, samples of special "stellite" bearings had been received and they were tested as part of the first "cold" testing.

The first unit tested used degreased all-stellite bearings and carbon brushes with a random silver impregnation. The assembly was set up in a vacuum and cooled to -10°C. Testing was set up for 15-minute runs, but the unit failed to start after its first run. Disassembly showed the brushes to be stuck in their holders, indicating that welding had taken place between the silver and the holder, causing the brushes to lose contact with the commutator. Brush wear was extremely rapid — .030 inch/hour. The bearings seemed unaffected by the test.

A similar test was set up with a unit assembled with stellite bearings, which, instead of a retainer, had hollow teflon "slugs" between the balls, and carbon brushes with a random MoS_2 impregnation. Test conditions were the same as for the previous test and this unit failed to start for its 5th run. The welding had occurred once more and the brush wear was catastrophic — at .037"/hour.

The following test was similar to the previous two, and involved all-stellite bearings and the MoS_2 core-lubricated brushes. This unit was started at -20°C. and failed to start for its second run. Brush wear was higher than normal at .002 to .004"/hour.

Another similar test was then set up using the teflon slug/stellite bearings and the MoS_2 core-lubricated brushes. It was started at $-30^{\circ}C.$ and performed well for 36 fifteen-minute runs, but failed to start for its 37th run. The brush wear was again relatively high at .002 inch/hour.

At this point all four "cold" tests had been ended by a loss of commutation, and no bearing trouble had been experienced. The latter two failures, both involving the MoS_2 lubricated brushes, were obviously not due to welding. The cause was undetermined at that time.

Gold-Plated Bearings with MoS_2 Brushes

The next test was the first cold test ($-30^{\circ}C.$) of the gold-plated bearings. They were assembled along with MoS_2 lubricated brushes in a motor and the unit was run under load. The unit was run as follows:

(1) 10 runs of 15 minutes;
(2) 55 runs of 30 minutes;
(3) Started and stopped 500 times to check response; and
(4) A continuous endurance run.

The total running time was 108-1/2 hours. In this case, failure was due to the separation of two commutator segments from the motor armature. The commutator had lost all its solder and the brushes were destroyed. The unit maintained a minimum of 9000 RPM for about 65 hours. Bearing performance was excellent even though both bearings had become heavily contaminated with carbon dust. This test indicated that the gold-plated bearings and the MoS_2 lubricated brushes would also meet the cold performance requirements of the EFM.

Special Tests of Crown Retainer Bearings

Another type of bearing received featured oil diffusion coated stainless steel components, and used a crown type retainer. Two types of stainless steel were used as a base material, so two tests were set up in the vacuum chamber, both using MoS_2 lubricated brushes. Both were run at $90^{\circ}C.$ to accelerate lubricant outgassing.

The first unit lasted for 5 runs, totaling 100 minutes. The running current was quite high and the solder was thrown from the commutator. The brush wear was unusual; one brush wore at .002 inch/hour and the other at .0003 inch/hour. The crown type retainer was distorted during the test, indicating that the bearing would be unacceptable for high-speed applications. This distortion and/or lack of lubrication probably caused the high running current.

D-1044

The second set of bearings was assembled in a similar unit. After 395 minutes of running, the rear bearing retainer spread excessively and jammed the bearing. This occurred during the 11th run, and the runs were characterized by a rapid temperature rise in the bearings and an increase in ambient pressure. The rise in pressure indicated a large outgassing rate for the lubricant. The running current was again quite high, indicating high friction in the bearings.

In preparation for EFM prototype testing, an almost fully automatic test setup was developed, which included: automatic continuous running current monitoring; automatic continuous temperature monitoring; automatic 24-hour-per-day motor operation (3 minutes on, 9 minutes off); speed checks by Lissajous-figure technique; and simulation of vehicle charge to check the unit's operation as a field meter.

Appendix B

Prototype Test Details

As soon as hardware became available, the first complete electric field meter was assembled. It included the Servo-Tek motor (modified by substituting degreased gold-plated bearings and MoS_2 lubricated brushes), a gold-plated housing, a gold-plated rotor (grounded to the housing with MoS_2 lubricated brushes), a matching gold-plated stator and a tachometer. It was bench-checked, vibrated, and set up in the vacuum chamber for environmental testing. Testing was programmed for 3-minute runs, with 9 minutes between runs.

After ten excellent three-minute runs, the motor running current and speed became erratic, and after the 13th run the unit was stopped for inspection. Disassembly revealed that the rear bearing had not been fully seated during assembly, and so during vibration it had started to come apart. This is possible since this type of bearing can take an axial load in one direction only.

A similar unit was then assembled using a new motor and a new set of bearings, and incorporating a bakelite bushing to shield the rear bearing from carbon dust coming from the brushes. After a bench check and vibration, the motor was set up for environmental testing. The unit's performance was excellent through about 100 hot (approximately 90°C.) runs, but showed signs of failing soon after refrigeration began. The unit's response to the cold was marked by a steady gradual increase in motor running current, and after 144 runs (7.2 hours running time) the test was stopped. The decreasing temperature had caused interference between the bakelite shield and the motor shaft, which resulted in an increased load on the motor. The effect of the additional load was to lower the speed of the motor, and subsequently its back emf, which resulted in a higher running current.

Another unit was assembled, which was identical to the previous one except that a teflon bushing was inserted in place of the bakelite bearing shield. The unit was vibrated and inserted into the vacuum chamber and after the first successful run, cold was applied. During the third run, the performance of the unit became erratic and the running current again started to rise. The test was halted after 12 runs. Again the drop in temperature had resulted in interference between the shield and the shaft which drastically affected the motor speed, although the contact was between the low-friction teflon and stainless steel. After this test, efforts to shield the rear bearing were dropped temporarily.

The next unit tested employed a new motor and a new set of bearings. It used the same pair of motor brushes which had been run in the three previous tests. During the prototype testing, the initial length of the brushes was controlled, but wear measurements were not made since the MoS_2 lubricated brushes had "proven themselves" for this application. This unit underwent a thermal-vacuum check before the vibration testing which included a thermal cycle (room temperature to 0°C. to 90°C. to room temperature), and consisted of 27 excellent runs. After vibration the unit was set up in the chamber. The performance of the unit was excellent for about 200 runs, at which time the motor running current began to rise. After 271 runs, it was stopped to investigate the trouble. During the operating time the ambient temperature had been cooled initially to 0°C, had been raised from 0° to 90°C six times, had been lowered from 90° to 0° five times, and had been below 0° overnight once. Disassembly revealed that the front bearing retainer had worn badly, making the bearing very rough. The bearing was sent to the manufacturer for study. This was the first failure experienced which could be traced to the gold-plated bearings. The excessive wear on the anodized aluminum retainer could possibly be attributed to either the use of fatigued material, or defective anodizing.

A new unit was assembled, incorporating a newly designed housing, the motor armature from the previous unit, new brushes, and a new set of bearings. It was also vibrated and set up for environmental testing. After an initial cooling to 0°C, the unit was accidentally overheated, causing a loss of solder from the motor armature and failure of the unit. A total of 38 runs were made and the performance was excellent while the temperatures remained normal.

The damaged armature was replaced and a test was started, using the same bearings and brushes. This unit was the first which was not vibrated prior to thermal vacuum testing. At this time it was felt that the EFM had been proven structurally sound and that further vibration of units would not be necessary. This test was run almost entirely at temperatures below 0°C and through the first 52 three-minute runs the performance of the unit was satisfactory except for a few brief running current fluctuations. The motor failed to start for run 53, however, and a check of the armature resistance revealed an open circuit which indicated a loss of commutation similar to that experienced in the previous motor testing. Again this phenomenon could not be explained.

Inspection of the unit revealed some wear on the front bearing retainer, so it was replaced by a bearing which had been run previously for about 8 hours but showed no signs of wear. A fresh pair of MoS_2 lubricated brushes was substituted for those run in the previous unit and testing was resumed. The performance of this unit was excellent through 185 runs (50 at -30°C, 110 at 90°C and 25 at 0°C) but failed rapidly as retainer wear stiffened the front bearing. The unit was stopped during run 189. This bearing came from the same set of bearings as the one whose retainer had failed previously and it appeared that all six of these bearings may have been defective. New bearings were requested from the manufacturer.

Although new bearings were not on hand, the availability of the testing facilities prompted further EFM testing to study the existing problem areas. A unit was assembled which included the two best available bearings, used brushes, the standard housing, rotor and stator, and a used motor armature. To make the testing of this unit more rigorous, a vibration was included after a preliminary thermal-vacuum check. The unit performed well during this check, which included a thermal cycle with -30°C and 90°C peaks and 20 three-minute runs.

After vibration, the unit was again set up in a vacuum and the testing commenced. The unit performed well through 120 runs and three thermal cycles, and then the running current became somewhat erratic and gradually increased. This trouble began during a run at 90°C. The temperature was then cycled from hot to cold to hot again and the performance became worse steadily. As 200 runs were completed, the running current had become very high and irregular, and after 210 runs the test was stopped. Disassembly revealed wear on the bearing retainers and some carbon contamination in the rear bearing. The bearing condition was responsible for the increased running current of the motor, and it had caused an overheating of the armature which had lost most of its solder.

No new bearings had been received, so the bearings were cleaned, the armature replaced and testing resumed. The performance of the unit was good for about 50 more runs and two thermal cycles, but during a long overnight period of 90°C temperature the running current began to rise and become irregular again. The current stopped rising when it reached a value of approximately twice the normal current and remained nearly constant during the remainder of the 100 90°C runs. The temperature was then lowered to 0°C and the performance of the unit did not change, so the test was again halted for inspection of the bearings and the armature. The rear bearing again was contaminated with carbon and both bearings showed additional signs of wear, but the solder on the armature seemed firm. Signs of wear were also evident on the sides of the rear bearing retainer. This led to the discovery of another factor in the bearing performance. At times the retainer was apparently riding against a step on the motor shaft which tended to restrict the "free-floating" of the retainer and introduced additional friction. This step on the shaft was chamfered to make this interference impossible. After the bearings were cleaned, testing was resumed.

This time the performance was good for only a few runs then the running current became irregular. After about 80 more runs and one thermal cycle, the motor failed to start. The circuit was open and the test was halted again.

After the vacuum chamber was opened and the rotor was turned by hand, it started. The roughness felt as the rotor was turned showed the effect of the retainer wear. The chamber was closed again and the test was resumed, but after about 50 more runs and two thermal cycles, it was apparent that the condition of the bearings made further testing useless. The performance of the unit was becoming continuously worse, so after a total of over 28 hours of running time, this test was abandoned. The test had shown that the latest shipment of bearings was definitely not of the same quality as those tested earlier, but also that the carbon contamination in the rear bearing was a factor affecting bearing performance. Brush performance had been excellent throughout the test, but another case of lost commutation had been experienced and could not be explained.

Since new bearings still had not arrived, another EFM was assembled using all tool steel bearings similar to those previously tested, a fresh pair of MoS_2 lubricated brushes, and a Kel-F washer as a shield for the rear bearing. Care was taken to avoid the possibility of interference between the shield and the shaft. The performance of this unit was poor initially and grew progressively worse through 83 runs and two thermal cycles. The test again showed the necessity of lubrication with these bearings. The extent of carbon deposits in the rear bearing indicated that the shield had been partially effective, however.

Another unit was assembled using old gold-plated bearings and new brushes, and incorporating a thin bakelite gasket which was cemented to the aft end piece of the motor as a bearing shield. This unit ran beautifully for 80 three-minute runs, mostly at room temperature, but then failed to start for run number 81. Again commutation had been lost. The MoS_2 lubricated brushes were removed and replaced by standard carbon brushes to study the resulting effect, and after 5 more runs, commutation was lost again.

A close examination of the motor revealed the cause of the occasional loss of commutation which had appeared during the test program. In the Servo-Tek motor the brushes are supported by two brass holders which have square holes in them. The edges of these holders were found to be sharp and slightly burred. As the armature of the motor turned, the brushes would move slightly up and down due to small irregularities of the commutator surface. Occasionally the side of a brush would dig into the sharp edges of the brass holder and become separated from the commutator, resulting in an open circuit. In future testing, the edges of the brush holders were rounded to prevent this occurrence.

Again in this test, the shielding was partially effective, and the bearings did not show any signs of wear.

Since the new bearings had not arrived, and no lubricated bearings had been run during the prototype testing, a unit was assembled using the standard bearings and brushes which are used in the Servo-Tek motor.

This test was intended to provide a standard to which the performance of the special bearings and brushes could be compared. A Kel-F washer, pressed in place, was used as a rear bearing shield. The unit ran well for about 10 runs, then the running current began to rise and later became quite irregular. During the 35th run the current rose sharply and became very erratic causing the test to be stopped. The unit had completed two thermal cycles and had been in a vacuum for about 20 hours. As the bearings dried out, the performance had deteriorated rapidly. Extreme brush wear had occurred and the shield again was partially effective. The excessive brush wear permitted a study of the carbon distribution in the motor. The motor housing had previously been ventilated to provide an escape path for the carbon into the EFM housing, where it would do no harm. The spacing of the ventilating slots had been determined by assuming that the carbon particles would fly off along a line tangent to the brush path on the commutator at the point of brush contact. The study of the carbon pattern in the motor showed that moving these slots to another position would increase their effectiveness, and that most of the carbon particles in the bearing had apparently bounced off the walls of the housing into the bearing.

Another test was then set up with a newly ventilated motor housing, used gold-plated bearings, new MoS_2 lubricated brushes, and another thin bakelite gasket which was cemented in place as a bearing shield. The performance of this unit was excellent during the first 110 runs and 4 thermal cycles, after which the running current began to rise. The remainder of the test was marked by a gradual increase in running current which eventually blew the circuit's 500 ma fuse. Four-hundred-ninety-two (492) runs were made, for a total of 24.6 hours running time, and the unit went through twelve complete thermal cycles which included three overnight cold (-30°C) runs and one overnight hot (90°C) run.

The failure of this unit was caused by wear on the rear bearing retainer. Brush performance was excellent and the combination of the re-designed ventilation and the bakelite gasket had effectively shielded the rear bearing, as very little carbon was found in it. Some solder had been thrown from the motor's commutator during the high current runs.

By the time a new shipment of bearings arrived, the EFM prototype design was finalized and two units were built for the satellite prototype testing. A third identical unit was fabricated for the last of the thermal vacuum tests – a check of the final prototype design. This unit incorporated an aluminum tape rear bearing shield and two of the new bearings. It was vibrated and placed in the vacuum chamber. This unit's performance was excellent through 300 three-minute runs (15 hours); but then, during a long series of runs at about -30°C, the running current became somewhat erratic. The performance became increasingly worse. After a total of about 400 runs, the running current was very high and unsteady. After 570 runs and 12 thermal cycles (-30°C to 90°C), the unit was inspected.

Disassembly revealed that the problem was a small amount of contamination in the bearings. Apparently the degreasing operation had not been entirely successful and as the remaining oil or grease dried out in the vacuum, the bearing friction increased excessively. The brushes looked good and no carbon was found in the bearings, indicating that the ventilation of the housing and the use of the aluminum tape shield was effective. The bearing retainers showed very little sign of wear, so the bearings were again degreased, and the unit was reassembled for further testing.

This unit was tested for a total of 608 more runs and 15 thermal cycles and its performance throughout was excellent. Three or four times the running current became slightly erratic but quickly settled down. Near the end, the current was higher than it was at the start but it was still within the acceptable range. The test was stopped in order to check the condition of the bearing retainers. Slight signs of wear were visible and the bearings were noisy but still in good running condition. The occasional inconsistencies in the running current were probably due to small fragments of the anodized aluminum retainer which did wear off during nearly 60 hours of operation.

The completion of this test marked the end of the EFM developmental testing. Periodically during the EFM prototype testing, the units were checked by the experimenter for their acceptability as field meters. All units functioned satisfactorily.

Appendix C

Brush Wear in a Vacuum

During the early stages of World War II, difficulties with electric generators were encountered in high flying aircraft. The rapid failure of the generators was caused by excessive carbon brush wear. The most notable among the investigators studying this wear problem were Dr. W. Campbell of Bell Laboratories, and R. H. Savage of General Electric. Dr. Campbell used a dry inert gas for his test environment and Mr. Savage a vacuum chamber. Both investigators reported that in order for the carbon brush to perform properly, there had to be an adsorb layer of moisture at the brush-copper interface. Without this adsorb layer of moisture, the brush surface was not lubricated and hence, excessive wear occurred. Mr. Savage* states that carbon brush wear is a function of the amount of water vapor present at the copper-carbon interface. The hardness of the edges of a carbon crystal is thought to be quite high, making these edges sources of abrasion unless they are lubricated. The unlubricated graphite crystals that are distributed in a random manner on the surface of a brush would tend to act as cutting tools when their edges come in contact with the commutator, and thereby cause a scored commutator and accelerated brush wear.

A lubricated carbon crystal shows apparent inactivity on both the edges and face as a result of adsorption of water vapor, and the crystals are quickly stroked into the commutator surface, forming a protective layer which appears as a glazed film. In an atmosphere essentially free from moisture, this layer will form only if the brush carries its own lubricant.

Various compounds have been tried as impregnation fillers for carbon brushes. Among the materials investigated were: barium flouride, molybdenum disulfide, silver, and copper.

Dr. Campbell, representatives of the Stackpole Carbon Company, and Mr. Hugh Campbell of General Electric Laboratories in Schenectady, New York, feel that of the above mentioned materials, MoS_2 would probably be the best. The General Electric data on MoS_2 -impregnated brushes, tested in a vacuum of 5×10^{-5} mm Hg, appeared encouraging. Apparently, the atomic lattice of the carbon and sulfur are compatible

*Savage, R. H., "Carbon-Brush Contact Film," G. E. Review 48(10):13-20, October 1945 and the sulfur has the ability to take the place of moisture in lubricating and aligning the carbon crystals in a manner that reduces wear. The glazed film that Mr. Savage mentioned is quite prominent with the MoS_2 impregnated carbon brushes that were used for the EFM study.

Appendix D

Bearing Wear in a Vacuum

The satellite environment includes a pressure much lower than the vapor pressure of any conventional lubricants and unlubricated ball bearings fail rapidly due to catastrophic wear. The standard bearings in the Servo-Tek motor had to be replaced.

Besides the usual greases and oils, some oxide films also have good lubricating qualities, but in the vacuum of outer space, oxidative repair cannot take place.* With the oxide layer broken, chemically clean metal comes into contact with other chemically clean metal and galling occurs.

To get a better understanding of the problem let us investigate the mechanism through which wear occurs. It is known that even though a surface is highly polished, a certain degree of roughness exists. Magnified many times this polished surface may resemble a mountain range. In a ball bearing, the surfaces of the races and the balls contain these "mountains" and "valleys." When two mountains come in contact, an area of extreme stress exists and hence these mountain tops are crushed.

The surfaces are initially covered with an oxide film and when crushing occurs the film is broken. In a vacuum environment oxides cannot be formed, hence a surface exists where chemically clean metal is exposed. When similar chemically clean metals come in contact with one another, adhesion takes place and galling occurs.

The three main avenues of approach to the solution of the bearing problem appear to be:

1. Use of solid dry film lubricants such as platings;

2. Use of layer lattice crystals employing a tenacious polar bond to the base metal; and

3. Use of dissimilar materials to minimize the tendency toward forming solid solutions when in contact.

Dry films seem to offer the best possibility for significant improvement in wear rates. Dr. W. E. Campbell has explained the theory of stress minimization behind the

*"Implications of Operating Instrument Bearings in the Vacuum of Outer Space," New Hampshire Ball Bearings Inc., Peterborough, N. H.